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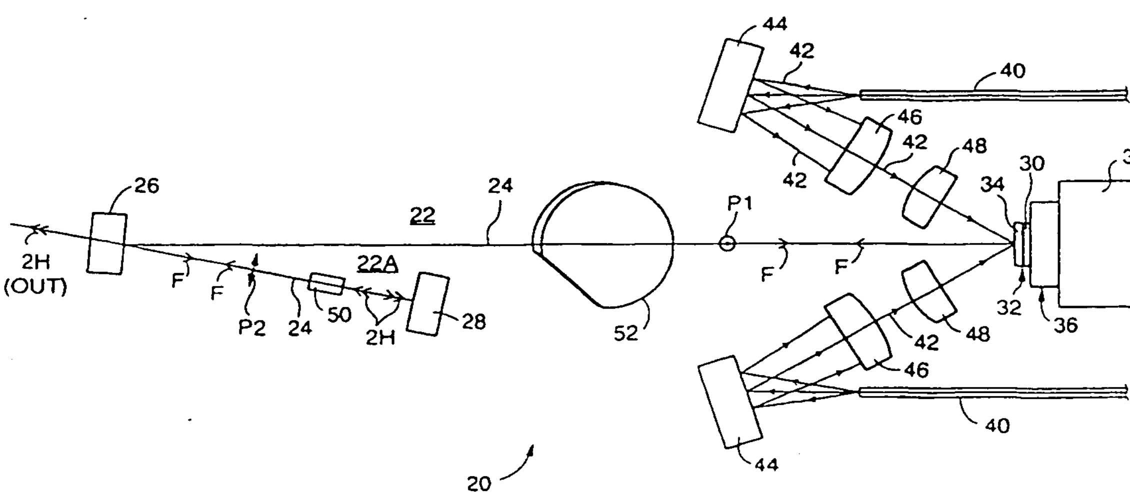


(57) Abstract

External–cavity optically–pumped semiconductor lasers (OPS–lasers) including an OPS–structure having a mirror–structure surmounted by a surface–emitting, semiconductor multilayer (periodic) gain–structure are disclosed. The gain–structure is pumped by light from diode–lasers. The OPS–lasers can provide fundamental laser output–power of about two Watts (2.0 W) or greater. Intracavity frequency–converted arrangements of the OPS–lasers can provide harmonic laser output–power of about one–hundred milliwatts (100 mW) or greater, even at wavelengths in the ultraviolet region of the electromagnetic spectrum. These high output powers can be provided even in single axial–mode operation. Particular features of the OPS–lasers include a heat sink–assembly for cooling the OPS–structure, a folded resonator concept for providing optimum beam size at optically–nonlinear crystals used for frequency conversion, preferred selection of optically–nonlinear materials for frequency–conversion, and compound resonator designs for amplifying second harmonic–radiation for subsequent conversion to third or fourth harmonic radiation.

HIGH-POWER EXTERNAL-CAVITY OPTICALLY-PUMPED SEMICONDUCTOR LASERS

TECHNICAL FIELD OF THE INVENTION

The present invention relates in general to external-cavity optically-pumped semiconductor lasers (hereinafter, OPS-lasers) including a surface-emitting, semiconductor multilayer (periodic) gain-structure. The invention relates in particular to arrangements of such lasers which can provide fundamental laser output-power of about two Watts (2.0 W) or greater, and intracavity frequency-converted arrangements of such lasers which can provide harmonic laser output-power of about one-hundred milliwatts (100 mW) or greater.

DISCUSSION OF BACKGROUND ART

The term OPS-lasers, as used herein, refers to a class of vertical-cavity surface-emitting semiconductor lasers wherein optical gain is provided by recombination of electrical carriers in very thin layers, for example, about 150 Ångstrom units (Å) or less, of a semiconductor material. These layers are generally termed quantum-well (QW) layers or active layers.

In an OPS-laser, several QW layers, for example, about fifteen, are spaced apart by separator layers also of a semiconductor material, but having a higher conduction band energy that the QW layers. This combination of active layers and separator layers may be defined as the gain-structure of the OPS-laser. The layers of the gain-structure are epitaxially grown. On the gain-structure is an epitaxially-grown

monolithic, device in keeping with the generally compact nature of semiconductor lasers and packaged arrays thereof.

The gain-structure of OPS-structures may be formed from the same wide range of semiconductor-materials/substrate combinations contemplated for diode-lasers. These include, but are not limited to, InGaAsP/InP InGaAs/GaAs, AlGaAs/GaAs, InGaAsP/GaAs and InGaN/Al_2O_3, which provide relatively-broad spectra of fundamental-wavelengths in ranges, respectively, of about 960 to 1800 nanometers (nm); 850 to 1100 nm; 700 to 850 nm; 620 to 700 nm; and 425 to 550 nm. There is, of course, some overlap in the ranges. Frequency-multiplication of these fundamental-wavelengths, to the extent that it is practical, could thus provide relatively-broad spectra of radiation ranging from the yellow-green portion of the electromagnetic spectrum well into the ultraviolet portion.

In conventional solid-state lasers, fundamental-wavelengths, and, accordingly, harmonics thereof (produced by frequency-doubling or frequency-mixing) are limited to certain fixed wavelengths characteristic of a particular dopant in a particular crystalline or glassy host, for example, the well-known 1064 nm wavelength of neodymium-doped yttrium aluminum garnet (Nd:YAG). While one of these characteristic wavelengths may be adequate for a particular application, it may not be the optimum wavelength for that application.

OPS-lasers provide a means of generating wavelengths, in a true CW mode of operation, which can closely match the optimum wavelength for many laser applications, in fields such as medicine, optical metrology, optical lithography, and precision laser machining. Prior-art OPS-lasers, however, fall

particular aspect, an OPS-laser in accordance with the present invention comprises an OPS-structure having a gain-structure surmounting a mirror-structure. The gain-structure includes a plurality of active layers having pump-light-absorbing layers therebetween. The active layers have a composition selected to provide emission of electromagnetic radiation at a predetermined fundamental-wavelength between about 425 nanometers and 1800 nanometers when optical-pump light is incident on the gain-structure. The mirror-structure includes a plurality of layers of alternating high and low refractive index and having an optical thickness of about one-quarter wavelength of the predetermined wavelength.

A laser-resonator is formed between the mirror-structure of the OPS-structure and a reflector spaced apart therefrom. An optical arrangement is provided for delivering the pump-light to the gain-structure, thereby causing fundamental laser-radiation having the fundamental wavelength to oscillate in the laser-resonator. A heat-sink arrangement is provided for cooling the OPS-structure. An optically-nonlinear crystal is located in the laser-resonator and arranged for frequency-doubling the fundamental laser-radiation, thereby providing frequency-doubled radiation having a wavelength half of the fundamental wavelength.

The laser-resonator, the optically nonlinear-crystal, the OPS-structure, the heat-sink arrangement and the optical pump-light-delivering arrangement are selected and arranged such that the resonator delivers the frequency-doubled radiation as output-radiation having a wavelength between about 212 nanometers and 900 nanometers at an output-power greater than about 100 milliwatts. The laser

Watts of pump-light at 670 nm, using a 5 mm-long LBO crystal for frequency doubling to provide output-power in excess of 1 Watt at the frequency-doubled wavelength of 375 nm.

This remarkable increase in OPS-laser output-power and the ability to generate high, CW, UV output-power, either by frequency-doubling or frequency-tripling, is achieved without sacrifice of beam-quality. Single mode operation provides that OPS-lasers in accordance with the present invention can have a beam quality less than 2.0 times, and as low as 1.2 times the diffraction limit. This high-beam quality makes the inventive OPS-lasers ideal for applications in which the output radiation must be focused to a very small spot for making precise incisions in inorganic or organic material, or must be efficiently coupled into an optical fiber for transport to a location where it is to be used.

In another aspect of an OPS-laser in accordance with the present invention, the laser includes first and second resonators arranged such that a portion of the resonator axes of each are on a coaxial path. The first resonator includes an OPS-structure arranged outside the coaxial path to provide a selected fundamental-wavelength of laser radiation. Located on the coaxial path of the first and second resonators is an optically-nonlinear crystal arranged for frequency-doubling the fundamental radiation. The first and second resonators are interferometrically matched to maintain optimum phase-matching between fundamental and frequency-doubled radiation in the optically-nonlinear crystal. Fundamental-wavelength radiation and frequency-doubled radiation circulate together only along the coaxial path. An optically-nonlinear crystal is located in the second resonator outside the coaxial

laser output-power; design of specific, folded-resonator configurations for optimizing output of frequency-converted radiation and preventing reflection of the frequency-converted radiation back into the OPS-structure where it would be lost through absorption; selection of a specific ratio of pumped area to mode-size at the OPS to optimize use of gain, and to prevent generation of transverse modes of oscillation; use of an intracavity wavelength-selective element for preventing oscillation of fundamental radiation at wavelengths outside the spectral range of acceptance of optically nonlinear crystals; selection of optically nonlinear materials for maximum spectral acceptance to allow the use of efficient and tolerant wavelength-selective devices for the former; configuration of OPS-structures to eliminate parasitic lateral oscillation which would otherwise reduce output power; design of OPS-structures for minimum net stress and reliability under high power operation; use of radial-index gradient lens to optimize multiple optical-fiber delivery of pump-light; and design of mirror-structures for the inventive OPS-structure for maximum thermal-conductivity thereby facilitating cooling of the OPS-structures.

It will be particularly evident from the detailed description of the present invention presented below that for achieving the high powers discussed above, OPS-laser resonators in accordance with the present invention depart radically from the "compactness" philosophy of prior-art OPS-lasers and are inventively configured for intracavity frequency multiplication. It will also be evident that significant attention is directed to thermal management of OPS-structures, to the design of OPS-structures themselves, and to selection of frequency

nonlinear crystals arranged for intracavity frequency-tripling the fundamental-wavelength of the OPS-structure.

FIG. 5. schematically illustrates yet another preferred embodiment of an OPS-laser in accordance with the present invention having a first resonator including an OPS-structure and a second resonator having a common optical path with the first resonator, the common optical path of the resonators including two optically-nonlinear crystals arranged for intracavity frequency-tripling the fundamental-wavelength of the OPS-structure.

FIG. 6 schematically illustrates still another preferred embodiment of an OPS-laser in accordance with the present invention having a first resonator including an OPS-structure and a second resonator having a common optical path with the first resonator, the resonators being arranged for intracavity frequency-quadrupling the fundamental-wavelength of the OPS-structure.

FIG. 7 schematically illustrates a further preferred embodiment of an OPS-laser in accordance with the present invention having a straight resonator including an OPS-structure and a birefringent filter.

FIG. 8 schematically illustrates the OPS-structure of any of FIGS 1 and 4-7 bonded to a heat-sink assembly in accordance with the present invention.

FIG. 1 schematically illustrates an OPS-laser 20 in accordance with the present invention. Laser 20 includes a resonator 22 having a longitudinal axis 24 thereof folded by a fold-mirror 26. Resonator 22 is terminated at one end thereof by a flat mirror or reflector 28, and at the other end thereof by a mirror portion (mirror-structure) 30 of an OPS-structure 32. A gain portion (gain-structure) 34 of OPS-structure 32 is thus located in the resonator in contact with a resonator mirror, *i.e.*, mirror-structure 30.

Gain-structure 34 of OPS-structure 32 is an epitaxially-grown monolithic semiconductor (surface-emitting) multilayer structure including a plurality of active layers (not shown in FIG. 1) spaced apart by pump-light-absorbing separator-layers (also not shown in FIG. 1). It should be noted here that the terminology "spaced apart by pump-light-absorbing separator layers" in the context of this description and the appended claims does not preclude there being other layers between the QW layers. Depending on the composition of the QW layers, one or more other layers may be included for strain-management, carrier-confinement and the like. Any such arrangement is applicable in the context of the present invention.

In prior-art OPS-lasers, the mirror-structure of the OPS-structure is typically also an epitaxially-grown multilayer structure grown from different compositions of material having a general composition $Al_xGa_{(1-x)}As$ (abbreviated AlGaAs), wherein increasing x increases the bandgap of the material, and lowers the refractive index. While this is one form of mirror-structure which could be used for mirror-structure 30, it is neither the only form contemplated, nor the preferred form contemplated. Mirror-structure 30 in

used without departing from the spirit and scope of the present invention.

Mirrors 26 and 28, and mirror-structure 30 of OPS-structure 32, each have maximum reflectivity at a fundamental (emission) wavelength characteristic of the composition of (active layers of) gain-structure 34 of OPS-structure 32. Energizing gain-structure 34 of OPS-structure 32 causes laser radiation having the fundamental-wavelength (fundamental-radiation) to circulate in resonator 22. This fundamental-radiation is indicated in FIG. 1 by single arrows F.

Included in resonator 22, in folded portion 22A thereof, proximate, but spaced apart from mirror 28, is an optically-nonlinear crystal 50 arranged for frequency-doubling (halving the wavelength of) the fundamental radiation. This generates frequency-doubled or second-harmonic (2H) radiation indicated in FIG. 1 by double arrows 2H. 2H-radiation is generated both on a first pass of fundamental laser radiation therethrough and on a return pass of the fundamental-radiation after it is reflected from mirror 28. Fold-mirror 26 is transparent to the 2H-radiation and, accordingly, serves to couple the 2H-radiation out of resonator 22.

It should be noted here, that this folded-resonator arrangement of an OPS-laser in accordance with the present invention is particularly important, considering the high-power operation of the device. The folded-resonator arrangement allows formation a resonating beam in resonator 22 having optimum characteristics at OPS-structure 32 and at the optically-nonlinear crystal 50. In one arrangement the pump-light spot-size at OPS-structure 32 preferably has a gaussian shape, preferably with a $1/e^2$ radius of about 230 micrometers (μm). In order to maximize overlap and obtain optimum power-

emphasized here that the purpose of this wavelength-selective element is not axial-mode selection, as this is accomplished by a combination of the unique properties of OPS-structure 32 combined with its location in resonator 22. Rather, birefringent filter 52 is used to effectively spectrally narrow the gain-bandwidth of gain-structure 34 of OPS-structure 32 to a bandwidth narrower than a spectral acceptance region over which the optically-nonlinear crystal 50 is effective. This prevents laser 20 from oscillating at wavelengths where the optically-nonlinear crystal is ineffective. This aspect of OPS-lasers in accordance with the present invention is also discussed in detail further hereinbelow.

In one example of a laser 20 in accordance with the arrangement of FIG. 1, OPS-structure 32 (see FIG. 3) has a gain-structure 34 comprising fifteen QW or active-layers of an $In_{0.18}Ga_{0.82}As$ composition, having a thickness of about 75.0 Angstrom Units (Å) providing a nominal fundamental (emission) wavelength of 976 nm. Between the QW layers are pump-light-absorbing (separator) layers of a $GaAs_{0.978}P_{0.022}$ composition having a thickness of 1217 Å. Between the QW layers and the separator layers is a strain-relieving layer of GaAs having a thickness of about 50 Å. Mirror-structure 30 comprises 27 pairs or periods of alternating layers of GaAs having a refractive index of about 3.51 and $AlAs_{0.96}P_{0.04}$ having a refractive index of about 2.94 and an optical thickness of one-quarter wavelength at the fundamental-wavelength. Gain-structure 34 also includes a carrier-confinement layer of $Ga_{0.51}In_{0.49}P$, having a thickness of 1588Å, between the last separator layer and mirror-structure 30. At an opposite extremity of gain-structure 34 there is also a carrier-confinement layer of $Ga_{0.51}In_{0.49}P$ having a thickness of 1588Å.

layer only without a gold overcoating. Bonding is then performed using indium solder. It is believed that such a bonding method would be superior to prior-art chip-bonding methods, not only under the high-power operating conditions contemplated for OPS-lasers in accordance with the present invention but for any OPS-laser.

Another possible bonding method would be to use a more stable, gold-tin eutectic solder rather than indium solder. It is possible, here, however, that a coefficient of thermal expansion (CTE) mismatch with diamond may limit its use with diamond heat-sinks. The CTE mismatch problem may be avoided by use of alternate heat-sink materials having a closer CTE match to the gold-tin eutectic, such as copper-tungsten (Cu-W), cubic boron nitride, silicon-diamond composite, and the like. Some compromise in output-power performance may be expected here, however, due to the lesser heat conduction efficiency of these materials compared to diamond. The CTE mismatch problem becomes greater the larger the chip.

After the OPS-structure is bonded to the diamond-layer/microchannel-cooler, the GaAs substrate is removed by etching. Preferably, an antireflection coating is deposited on thus-exposed gain-structure 34 to improve entry of pump-light into the gain-structure.

Regarding optical pumping of OPS-structure 32, each fiber 40 delivers about 17.0 W of 795 nm radiation from a FAP-30C-800-B diode-laser-array package available from Coherent Semiconductor Group of Santa Clara, CA. Mirrors 44 are dielectric-coated mirrors having greater than 99.9% reflectivity at 795 nm and 28° angle of incidence. Lenses 46 are cemented doublets having a focal length of 40.0 mm and a diameter of 18.0 mm. Lenses 48 are cemented

distance of 202 mm. Mirrors 26 and 28 are axially separated by a distance of 56 mm. Accordingly, resonator 22 has an axial length of 258 mm (25.8 cm).

Optically nonlinear crystal 50 is a 5 mm-long crystal of lithium triborate (LBO) having a cross-section of 3 mm x 3 mm. The crystal is cut for type-1 phase matching for 976 nm radiation. Propagation of the fundamental beam is in the crystallographic X-Y plane. The propagation direction is at an angle of 17.1 degrees from the X-axis. The fundamental-radiation is polarized perpendicular to the X-Y plane (parallel to the Z-axis). Second-harmonic radiation is polarized in the X-Y plane, as illustrated by arrow P2.

The above-specified exemplary OPS-laser generated an intracavity power of fundamental (976 nm) radiation of about 300 watts yielding frequency-doubled (488 nm) radiation at an output power of 5 Watts in single longitudinal (axial) mode and single transverse mode. The beam divergence was measured at 1.2 times the diffraction limit ($M^2 = 1.2$). The quantity M^2 is a numerical measure which represents a ratio of the size of the beam to a diffraction-limited size. A high quality beam may be regarded as a beam having an M^2 of about 2.0 or less. The high-beam quality available with the inventive OPS-lasers make them useful for applications in which the laser output-radiation must be focused to a very small spot for making precise incisions in inorganic or organic material, or must be efficiently coupled into an optical-fiber or guided by an articulated arm for transport to a location where it is to be used.

From the power point-of-view alone, this represents about a one-thousand-fold increase over the above-discussed 6.0 mW output of a prior-art IC, frequency-doubled OPS-laser. Surprisingly, the

improvement in the "electrical-to-optical" efficiency of two orders of magnitude for 488 nm lasers.

Continuing now with the description of preferred embodiments of OPS-lasers in accordance with the present invention, an important aspect of the above-discussed example of an OPS-laser is the discovery that such a high-fundamental power can be generated from an OPS-structure, by paying attention, inter alia, to thermal management of the intensely-pumped OPS-structure in combination with increasing the dimensions of the resonator well beyond those of prior-art OPS-lasers.

Having established experimentally that such a high fundamental and 2H-power can be provided, it is possible to numerically-model other inventive OPS-lasers based on the same or different OPS-structures 32 and "long resonator" arrangements, similar to that of laser 20, which generate other fundamental and 2H wavelengths at similar output power.

In particular, high-power CW radiation in the ultraviolet spectral region, for example, at about 375 nm, can be generated by using an OPS-structure 32 having a gain-structure 34 having $In_xGa_{1-x}P$ quantum wells with $In_yGa_{1-y}As_zP_{1-z}$ separator layers therebetween. Such an OPS-structure, pumped with 670 nm radiation from fiber-coupled diode-lasers (for example, SDL part number 7470 P-5 from SDL, Inc., of San Jose, CA) provides gain at 750 nm. A resonator similar to resonator 22 of FIG. 1 may be used, with a similar birefringent filter 52, suitably angle-tuned, and with an optically-nonlinear crystal 50 of LBO arranged for frequency doubling the 750 nm radiation. In this regard, the LBO crystal is preferably cut for propagation in the X-Y crystallographic plane, at an angle of 37.5 degrees from the X-axis. The polarizations of the fundamental and 2H-radiation are

configure other "long-resonator" type, inventive OPS-lasers based on the same OPS-structures, for generating third harmonic (3H) and fourth harmonic (4H) radiation, and to compute, with confidence, what output-power can be generated at such third and fourth harmonic-wavelengths in the UV region of the electromagnetic spectrum. Descriptions of such resonator configurations are set forth below, exemplifying generation of the third harmonic of 750 nm radiation, and the fourth harmonic of 976 nm radiation.

Referring now to FIG. 4, a laser 60 including a resonator 23 is schematically illustrated. Laser 60 is identical in most regards to laser 20 of FIG. 1, with the following exceptions. Mirror 28 is coated for high reflectivity at the fundamental and second (2H) harmonic wavelengths. Mirror 26 is maximally reflective at the fundamental-wavelength and highly transmissive at the 2H and 3H-wavelengths. An optically-nonlinear crystal 62, is located between optically-nonlinear crystal 50 and mirror 26 in folded arm 23A of resonator 23. Optically-nonlinear crystal 62 is arranged to mix the fundamental and 2H wavelengths (frequencies), thereby generating frequency-tripled radiation, indicated in FIG. 4 by triple arrows 3H. Both 2H and 3H-radiation leave resonator 23 via fold-mirror 26. The 2H and 3H-radiations are then separated by a dichroic beamsplitter 64.

Now, third-harmonic generation (mixing of fundamental and 2H frequencies) is known to be proportional (dependent on optically-nonlinear crystal characteristics) to the product of the fundamental and second-harmonic power. So, based on experimentally established values for these powers in this resonator, and on documented values for 3H-

nonlinear crystal 62. This may be achieved by a birefringent quartz plate (polarization rotator) of such design that it has retardation of an even integer multiple of π for the fundamental radiation, and retardation of an odd integer multiple of π for the 2H radiation.

Such a polarization-rotator (depicted in FIG. 4 in phantom as polarization-rotator 65) is inserted in the common path (arm 20A) of the fundamental and 2H-radiation between optically nonlinear crystals 50 and 62. Polarization-rotator 65, leaves the polarization of the fundamental-radiation unaltered, and rotates the linear polarization of the 2H-radiation by an amount equal to twice the angle between the initial polarization and the direction of the optic-axis of the retardation plate.

As an alternative, a BBO crystal may be cut for type-II mixing, so that polarization-rotator 65 is not required to modify the polarization of the 2H-radiation. Conversion in this case, however, can be expected to be less efficient.

Providing a resonator mirror or reflector on any optically nonlinear crystal in a OPS-laser resonator in accordance with the present invention is not precluded. However, additional measures such as temperature control of the crystal may be required to resolve the conflicting alignment requirements for the resonator and the cyrstal.

In resonator 23 of FIG. 4, third-harmonic generation from 970 nm fundamental-radiation is also possible using the alternatives discussed above for 750 nm fundamental radiation. Numerical simulations indicate that such third-harmonic generation could generate about 150 mW of 325 nm radiation. Those skilled in the art, from the above discussed example can determine appropriate nonlinear crystal

other end thereof by a mirror 74. Resonator 27 is also folded by a fold-mirror 26. Fold-mirror 26 in this embodiment is coated for maximum reflection at the fundamental and 2H-wavelengths and maximum transmission at the 3H-wavelength. Mirror 28 in this embodiment is coated for maximum reflection at the fundamental, 2H and 3H-wavelengths. The axes of the resonators are folded together by a dichroic beamsplitter 72 coated for maximum reflection at the 2H-wavelength and maximum transmission at the fundamental-wavelength. Accordingly, the common (here, folded) axial path of resonators 25 and 27 extends between beamsplitter 72 and mirror 28. It is pointed out here, that all coatings mentioned above are believed to be within the capabilities of commercial suppliers of optical coating services. One such supplier is Coherent Auburn Group, of Auburn, California.

Located in the common axial-path of resonators 27 and 27, proximate beamsplitter 72, is an optically-nonlinear crystal 50 arranged for doubling the fundamental-wavelength. The 2H-radiation generated by the frequency-doubling circulates and builds up in resonator 27, thereby greatly increasing the amount of intracavity 2H-radiation compared with the simple "double-pass" arrangement of laser 20 of FIG. 1. Located in common, folded portion 27A of resonators 25 and 27, (wherein, of course, both fundamental and 2H-radiation are circulating) is an optically-nonlinear crystal 62 arranged for mixing the fundamental and 2H-radiation to generate 3H-radiation. 3H-radiation so generated escapes the resonators via fold-mirror 26. Regarding the resonators in general, the following should be noted.

It is preferable that resonators 25 and 27 have about the same length and are similarly optically

As noted above, third-harmonic generation is proportional to the product of the fundamental and second-harmonic power. By incorporating a second resonator for 2H-power, laser 70 provides that a much greater 2H-power is available for mixing than is the case in laser 60 of FIG. 4, and, further, without any increase being required in the fundamental-power. So, based on above-discussed values for available fundamental-powers in this resonator and documented values for 2H-generation efficiency of LBO it can be numerically determined that 300 W of circulating 750 nm radiation would generate about 200 W of circulating 375 nm radiation in resonator 27. The double-pass combination of these in an optically non-linear crystal 62 of β-barium BBO can generate about 4 W of true-CW, single-mode, laser output-power at a wavelength of 250 nm. Similar output-power levels for 325 nm radiation can be determined for 3H-conversion of 976 nm radiation. This is a more than a six-hundred-times increase in power on third-harmonic generation over the maximum believed to have been reported for only second harmonic generation in prior-art OPS-lasers.

An optically-nonlinear (mixing) crystal preferable for laser 70 is the same as that discussed above with reference to laser 60. Care should be exercised in the design of resonator 25 of laser 70, however, in particular concerning the sizes of the beams within the optically-nonlinear crystals 50 and 62.

The fundamental and 2H-beams are preferably focused tightly in optically nonlinear crystal 62 to maximize conversion (mixing) efficiency. An optimum range of larger beam sizes, however, is preferred for fundamental-radiation in optically-nonlinear (doubling) crystal 50. Extensive numerical modeling

fold-mirror 94. Mirror 28 in this embodiment is coated for maximum reflection at the fundamental-wavelength. Mirror 74 is coated for maximum reflection at the 2H-wavelength. Mirror 92 is coated for maximum reflection at the fundamental, 2H, and, fourth harmonic (4H) wavelengths. Mirror 94 is coated for maximum reflection at the 2H-wavelength and maximum transmission at the 4H-wavelength

The axes of the resonators are folded together by dichroic beamsplitters 72 and 73, each thereof coated for maximum reflection at the 2H-wavelength and maximum transmission at the fundamental-wavelength. Accordingly, the common axial-path of the resonators 29 and 31 extends only between beamsplitters 72 and 73. For reasons discussed above, mirror 74 is mounted on a driver 76 controlled by a controller 82 in accordance with power detected by detector 80 to interferometrically-match resonators 29 and 31.

Optically-nonlinear crystal 50 is arranged for frequency-doubling fundamental-radiation circulating along common path 37 of resonators 29 and 31. Frequency-doubled radiation so generated circulates and builds up in resonator 31. Another optically-nonlinear crystal 67 is located in folded portion 31A of resonator 31 between mirrors 92 and 94 thereof. Optically-nonlinear crystal 67 is arranged for frequency-doubling circulating frequency-doubled radiation 2H thereby generating frequency-quadrupled (4H) radiation. The 4H-radiation exits resonator 31 via fold-mirror 94.

Such a resonator configuration is advantageous in the generation of 244 nm radiation through fourth-harmonic generation of 976 nm. A preferred optically-nonlinear (doubling) crystal 50 for this application is an LBO crystal having a length of

the optically-nonlinear crystal 67, to a spot-size of about 50 microns ($1/e^2$ radius).

Another preferred material for optically-nonlinear crystal 67 is cesium lithium borate (CLBO). This material can advantageously substitute BBO for frequency-doubling 488 nm radiation in this and other applications. A CLBO crystal for frequency-doubling 488 nm radiation is preferably cut for propagation of the beam at an angle of 75.7 degrees from the Z-axis, in a plane containing the Z axis and at an angle of 45 degrees from the X-Z plane. The 244 nm radiation so generated is polarized in the plane defined by the direction of propagation and the Z-axis (extraordinary polarization), the 488 nm radiation is polarized perpendicular to the 244 nm radiation. The nonlinear-efficiency of CLBO for this application is the same as that of BBO. CLBO, however, has a significant advantage of a five-times-greater angular acceptance than BBO, and a four-times smaller walk-off angle than BBO. A greater acceptance angle and smaller walk-off angle both contribute to increasing the net conversion-efficiency of an optically nonlinear crystal. First order considerations of acceptance angle and walk-off angle indicate that the conversion-efficiency of CLBO may potentially be several times higher than the efficiency of BBO. These first-order considerations are applicable in general to frequency-doubling radiation having a wavelength between about 425 nm and 525 nm in any resonator. The radiation in that wavelength range may be the fundamental-radiation or harmonic radiation of any gain-medium.

While embodiments of high-power OPS-lasers in accordance with the present invention are described above with respect to intracavity frequency-multiplication arrangements, it will be evident to

disclosure of which is hereby incorporated by reference.

Proceeding now with a description of mode-control and other scaling aspects of the present invention, a surprising discovery was that single axial-mode operation of the inventive lasers was simply achieved even at the relatively long resonator-lengths required for the exemplified high-power operation. The long resonator length is required for reasons, inter alia, as follows.

The gain-structure of an OPS has some inherent limitations due to the need to strongly absorb pump-light in layers separating the QW layers. These QW layers are preferably optically-spaced apart by a half-wavelength of the fundamental radiation. Prior-art investigations of such structures seem to have resulted in a general belief among practitioners of the relevant art that a number of about fifteen such QW layers is about optimum. This results at least from a consideration that the pump-light, through absorption in the structure, may not penetrate effectively more than fifteen half-wavelengths deep. It should be noted here that use of gain-structures with 15 QW layers in examples of OPS-lasers in accordance with the present invention should not be construed as limiting the inventive OPS-lasers or indicating that optimization of the depth and QW content of such gain-structures has reached a limit. In developing the inventive OPS-lasers, emphasis has simply been placed, with evident success, at addressing other scaling issues and other structural issues of OPS-structures. A discussion of such other issues is set forth below.

Considering, for the purposes of this description that some limit, whatever it is, to the depth or QW layer content of OPS gain-structures

In above-mentioned prior-art DPSS-lasers, as the length of a resonator is increased, the number of possible axial (longitudinal) modes of oscillation is also increased, absent any measures for preventing this. It would also be anticipated, on prima facie consideration, that this problem would exacerbated in an OPS-laser because of the greater gain-bandwidth of a semiconductor gain-medium compared with a solid-state (dopant:host) gain-medium of a DPSS-laser.

Typically, a large number of axial-modes leads to a fluctuating (noisy) power output as the modes compete chaotically for gain in the gain-medium. Prior-art measures which have been taken in DPSS-lasers to limit the number of oscillating modes and reduce output-noise include selective placement of the gain-medium in the resonator in positions where phase-relationships between adjacent modes limit this mode-competition. This approach has met with only limited success in prior-art DPSS-lasers. It is believed that, practically, true single mode operation has only been possible in prior-art lasers by mechanically stabilizing the resonator and including a highly wavelength-selective element in the resonator, with its attendant problems of resonator loss, maintenance of tuning, and the like.

Surprisingly it has been found that single axial-mode operation is possible in a high power OPS-laser in accordance with the present invention apparently independent of the physical length of the resonator, at least up the 25 cm length of the above exemplified inventive laser. It is believed that this length could be significantly further extended, for example, up to 100 cm or greater, while still maintaining single-axial-mode operation without any special provision for providing such operation.

other transverse-modes of oscillation of different frequencies while still deriving maximum gain from the pumped area.

Above-described OPS-lasers in accordance with the present invention have been described in terms of having physically long resonators, it being understood here, that what is referred to as resonator-length is the axial-length or distance between resonator end-mirrors. One skilled in the art, however, will recognize that increasing the physical resonator length is not the only way to provide for a large mode-size in the gain-structure 34 of OPS-structure 32 for increasing power. Incorporating a suitable optical system within a resonator can produce a large "equivalent length" for the resonator, even when the actual (physical) length of the resonator is relatively short. This may be used to provide a large spot-size at an OPS-structure in accordance with the present invention with a resonator having a relatively short physical length. An example of such a resonator arrangement used in a prior-art, flashlamp-pumped Nd:YAG laser, employing a telescopic arrangement of lenses in the resonator, is described in a paper by Hanna et al., Opt. Quantum Electron. 13, 493 (1981).

Ray optics considerations indicate, however, that in any such complex resonator, wherein a mirror-structure 30 of an OPS-structure 32 forms at one extremity of the resonator, the complex resonator is equivalent (as seen from mirror-structure 30) to a simple resonator consisting of a mirror (generally curved) placed at a specific distance from mirror-structure 30 of the OPS-structure 32. In other words, any arbitrarily complex resonator can always be reduced, for the purpose of determining mode-size at gain-structure 34 of OPS-structure 32, to an

Accordingly, a discussion of some important aspects of the thermal management is set forth below with reference to FIG. 8. FIG. 8 depicts, in detail, OPS-structure 32 and heat-sink 36 on which it is bonded.

The thermal-management problem may be summarily defined as follows. Pump-light 42 is absorbed in gain-structure of OPS-structure 32. That portion of the absorbed pump-light which does not generate electrical-carriers, *i.e.*, does not provide laser-radiation, generates heat in gain-structure 34. This heat must be conducted away by heat-sink 36 at a rate sufficient to keep the temperature of gain-structure preferably below a temperature of about 90°C. It should be noted here that this temperature is merely provided for guidance and should not be considered critical or limiting.

Mirror-structure 30 impedes the conduction of heat from gain-structure 32 to heat-sink 36. As discussed above, in a preferred, inventive heat-sink arrangement, OPS-structure 32 is bonded, by a solder layer 110, to a layer 112 of synthetic diamond, preferably having a thickness of about 0.3 mm. Diamond-layer 112, in turn is bonded, by another solder layer 114, to a copper-bodied microchannel-cooler 116.

In developing a heat-sink configuration for OPS-structure in accordance with the present invention, consideration was first given to the heat-sink properties of massive substrates of copper and diamond. From calculations considering the pump-power density provided by the above exemplified 34 W of pump-power delivered directly on the surface of a massive (essentially infinite in extent) copper heat-sink it was estimated that surface temperature on such a heat-sink would be 110°C. In practice, the 34 W of pump power would not be delivered directly to

above identified levels merely a matter of increasing resonator length. On closer investigation, however, this proves not to be the case.

By way of illustration of the pumped-area scaling problem, FIGS 9 and 10 depict computed isothermal contours (assuming radial symmetry) in respectively a relatively-massive (1.0 mm-thick) copper heat-sink and in a 0.3 mm-thick CVD-diamond layer bonded on a 0.7 mm-thick copper-heat-sink. The isothermal contours represent response to a uniform surface heating at a rate Q of 180 Watts per square mm (W/mm^2) within a circle H of 0.25 mm radius. (corresponding to the above-exemplified pump-power density on OPS-structure 32). Isothermal contours are at 5°C intervals. The terminology "relatively massive", as used above, means in relationship to the dimensions of OPS-structure 32.

It can be seen from both FIGS 9 and 10 that the temperature rises from edge to center of the heated (pumped) area. Increasing the pumped-area at the same pump-power density, accordingly, would increase the peak temperature of the OPS-structure. Fortunately, however, this increase is proportional to the square-root of the increase in area. This allows some trade-off between pump-power density and increasing pumped-area.

The effectiveness of the CVD-diamond layer, of course is also evidenced by the lower peak temperature of between 45°C and 50°C achieved with the diamond layer (see FIG. 10) compared with a peak temperature of about 100°C without the CVD-diamond layer (see FIG. 9).

Synthetic diamond in single crystal form has twice the thermal-conductivity of the CVD form. Accordingly, by substituting a single crystal diamond layer for the CVD-diamond layer a further surface

single-crystal diamond instead of CVD diamond would reduce this already small thermal lensing by a factor of two. Such low thermal-lensing simplifies considerably the design of the laser resonator. Generally, in designing a resonator for an OPS-laser in accordance with the present invention, it may be assumed that there is will be no thermal lensing.

Turning now to the heat-transfer-impeding effect of mirror-structure 30 of OPS-structure 32, in the example of the inventive OPS-laser discussed above, the total thickness of mirror-structure 30 of OPS-structure 32 is about 4.1 μm. Computations, based on this total thickness; bulk thermal-conductivity values of GaAs and AlAsP; and the structure of cooled-substrate 36 as depicted in FIG. 6, indicated that because of the heat-transfer-impeding effect of mirror-structure 30, the temperature of gain-structure 34 would be between about 18°C and 20°C higher than would be the case, were the gain-structure directly-bonded to diamond layer 112 of cooled-substrate 36. Accordingly, a substantial portion of the potential reduction in surface temperature offered by the bonded diamond layer is sacrificed to the mirror-structure. From experimental observations of the shift of the fluorescence spectrum of gain-structure 34 under the operating conditions of the above described practical example of inventive OPS-laser, it has been determined that gain-structure 34 is at a temperature of about 90°C.

It is clear, that an improvement in the thermal-conductivity of mirror-structure 30 of OPS-structure 32 could allow a higher pump-power to be delivered to gain-structure 32. This would allow further increases in output-power. Some approaches to

A metal layer in a mirror-structure 30 in accordance with the present invention would be the last-deposited (mirror) layer and would be furthest from the gain-structure. As this metal layer, in a completed OPS-structure 32, would be in direct contact with the heat-sink, it is believed that at least 0.1 percent absorption would be tolerable.

By way of example, using the GaAs and AlAsP materials exemplified above, with a 1000 Å layer of gold as the final layer, 99.9% reflectivity could be provided by a structure having only nine pairs of GaAs and AlAsP layers . Such a structure would have a total thickness of only about 1.47 μm, *i.e.*, about one-third the thickness of the mirror-structure of the above-described example. Accordingly up to a three-fold increase in thermal-conductivity of the mirror-structure as a whole can be anticipated.

It is believed that further reductions in thickness could be possibly be obtained by using a material having a much lower refractive index than AlAsP as a low refractive index material, for example, barium fluoride (BaF_2) having a refractive index of about 1.48. Using a 1000 Å-thick layer of gold as a final layer, 99.9% reflectivity could be provided by a mirror-structure 30 having as few as two pairs of GaAs and BaF_2 layers. Such a mirror-structure would have a total thickness of only about 0.54 μm, *i.e.*, about one-eighth the thickness of the OPS-structure of the above described example. What is gained in thermal-conductivity by the total thickness reduction, however, will be at least partially offset by the lower conductivity of BaF_2 compared with AlAsP and the greater physical thickness of BaF_2 required to provide one-quarter wavelength optical thickness at the fundamental-wavelength.

now to FIG. 11, an OPS-structure chip (designated here, for consistency by reference numeral 32) formed as described above, has what may be termed as an emission face 119 on gain-structure 34 and has smooth end-faces 120 in resulting from the scribe-and-break dicing method. End faces 120 are at right angle to emission-face 119 and have a relatively-high Fresnel reflectivity (about 30%) due to the relatively-high refractive index of semiconductor materials of the gain-structure. At operating powers contemplated for OPS-lasers in accordance with the present invention, absent any preventive arrangements, laser action can take place laterally (indicated in FIG. 11 by arrows B) in resonators formed by parallel pairs of end-faces 120.

During operation, such parasitic lateral oscillation would rob gain-structure 34 of OPS-structure 32 of gain which would otherwise be available for providing laser-action in the intended, surface-emitting direction (indicated in FIG. 11 by arrows C). Certain measures may be taken to suppress such parasitic lateral oscillation. One such measure comprises employing a dicing method wherein the wafer is cut or scribed completely from one side to the other with a diamond-scribe, diamond-saw, or like abrasive-cutting device. Following such scribing, end-faces 120 will be sufficiently rough or irregular that they are ineffective as mirrors. Accordingly, parasitic lateral oscillation will effectively suppressed. Other methods of roughening the end faces are not precluded.

If end-faces 120 are left smooth as a result of scribe-and-break dicing, coating the end-faces with a simple antireflection coating of material having a lower refractive index than the end-faces, such as aluminum oxide (Al_2O_3) or yttrium oxide (Y_2O_3), can

is included in a resonator formed between the mirror-structure of an OPS-structure and a (external to the structure) conventional mirror. A particularly preferred optically-nonlinear crystal material for IC frequency converted OPS-lasers in accordance with the present invention is LBO.

Because of the limited power available in prior-art OPS-lasers, it has been the practice in such lasers to use an optically-nonlinear material with as high a frequency conversion-efficiency as possible, typically, $KNbO_3$. $KNbO_3$, however, has certain disadvantageous properties that make it a less-than-ideal choice for use in a high-power frequency-doubled laser in accordance with the present invention. These disadvantageous features are a certain fragility, and a limited spectral-acceptance range. The spectral-acceptance range of an optically-nonlinear material is that range of wavelengths which would be frequency-converted for a crystal of the material.

FIG. 12 depicts the computed, normalized spectral-acceptance of $KNbO_3$, and of the significantly-more-durable, but less efficient, LBO. Each is assumed to be in the form of a 5 mm-long crystal. Also depicted is the gain-bandwidth of active layers of InGaAs having a composition selected to provide laser action around 976 nm. It can be seen that the spectral-acceptance of the $KNbO_3$ is about one-tenth that of the LBO, and is very narrow by comparison with the gain-bandwidth of the active layers.

Now, as the frequency-doubling mechanism of an intracavity optically-nonlinear crystal represents a loss for the fundamental-wavelength, absent any other constraint, the resonator will tend to shift (hop) its oscillation wavelength to a wavelength where

value of d_{eff} for $KNbO_3$ is about ten-times greater than the value of d_{eff} for LBO, then, in theory at least, a 0.5 mm-long $KNbO_3$ crystal would have the same peak SHG-efficiency and spectral-acceptance as a 5.0 mm-long LBO crystal. It is believed, however, that because of the fragility of the KNbO3, a 0.5 mm long KNbO3 crystal may be somewhat impractical to fabricate and handle. The use of KNbO3 crystals in resonators in OPS-laser resonators in accordance with the present invention, however, is not precluded.

Generally, for reasons discussed, above LBO and chromium lithium triborate (CLBO) are preferred for frequency-doubling and, alternatively, for frequency tripling. BBO is preferred for frequency quadrupling and, alternatively, for frequency tripling. For doubling or tripling wavelengths shorter than about 670 nm, optically nonlinear materials including strontium barium borate (SBBO), strontium borate (SBO), and barium zinc borate (BZBO) are believed to be effective. These optically-nonlinear material preferences should not, however, be considered as limiting IC frequency-converted lasers in accordance with the present invention.

TABLE 1

Bragg Mirror	QW/Separator	Subs-trate	Fundamental Wavelength (nm)
1	$In_xGa_{1-x}As/GaAs_yP_{1-y}$	GaAs	900 - 1050
2	$In_xGa_{1-x}P/In_yGa_{1-y}As_zP_{1-z}$	GaAs	700 - 900
3	$InAs_xP_{1-x}/InGa_yP_{1-y}$	InP	930 - 1800

TABLE 2

	Bragg Mirror Materials

of the first-listed family of structures wherein GaAs "transition" layers between the QW and separator layers, alleviate the stress-difference which would otherwise exist between these layers. The gain-structure of the OPS-structure of FIG. 2 can be generally categorized as being formed from components of the III-V quaternary system InGaAsP wherein the substrate material is a binary III-V compound of the components (here GaAs), and wherein the QW layers are formed from a one possible ternary III-V compound including both components of the substrate material, and the separator layers are formed from the other possible ternary III-V compound including both components of the substrate material. Type 3 structures of TABLE 1 (on InP substrate material) also fall into this category. This is believed to provide the optimum stress compensation for OPS structures formed from this quaternary system. For type 3 structures of Table 1 a mirror-structure including dielectric materials is preferable. One preferred structure includes high refractive index layers of zinc selenide (ZnSe) and low refractive index layers of aluminum oxide. This combination provides about the same reflectivity per number of layer-pairs as the combination of TiO_2 and SiO_2 used in general coating applications in the prior-art, but with a lower total physical thickness and higher thermal conductivity. It is emphasized here that the mirror structures of TABLE 2 are preferred structures for use with QW/separator structures of TABLE 1, the use of other mirror structures with the QW/separator structures of TABLE 1 in OPS-lasers in accordance with the present invention is not precluded.

Further, from the description of inventive OPS-lasers provided above, those skilled in the art may select other OPS-structures for providing

of OPS-structure 32 and at the other end thereof by a mirror 28. Resonator 130 includes a birefringent filter 52 for reasons discussed above. The OPS-structures are mounted on above-described heat-sink assemblies 36. Resonator axis 132 is folded once by mirror-structure 30X of OPS-structure 32X, and again by a fold-mirror 26. An optically-nonlinear crystal 50, arranged for frequency-doubling, is located in arm 130A of resonator 130, *i.e.*, between fold-mirror 26 and end mirror 28. Mirror 28 is coated for maximum reflectivity at the fundamental-wavelength. Mirror 26 is coated for maximum reflectivity at the fundamental-wavelength and maximum transmission at the 2H-wavelength.

It should be noted here that the tight folding of the resonator is selected to maintain as close to normal incidence as possible on OPS-structure 32X. This is to minimize interference in gain structure 34X between counterpropagating fundamental beams. Such interference can lead to the formation of interference-fringes (a sort of "lateral spatial hole-burning") in the plane of the QW layers, thereby limiting gain extraction from these layers. In this regard, it is also preferable to adjust spacing of the QW layers in gain-structure 34X and the thickness of layers of mirror-structure 30X to compensate for the effective refractive index change due to non-normal incidence, thereby maintaining effective half-wavelength spacing of the QW layers.

Continuing with reference to FIG. 13, a further difference between laser 128 and other above described OPS-lasers in accordance with the present invention is the manner in which pump-light is delivered to the OPS-structures. In laser 128, pump-light is transported along fibers 40 as in other above-described embodiments. Fold-mirror 44 and

and optical-pumping arrangements are the same as described above for laser 128. Laser resonator optionally includes a birefringent filter 52.

The laser-resonator arrangement of laser 140 may be useful if it desired to configure a laser-resonator which is terminated by two non-flat mirrors. It will be evident from the arrangement of laser 140 that similar arrangements wherein a resonator is not terminated at one end thereof by a mirror-structure of an OPS-structure may be devised for any other above described embodiments of OPS-lasers in accordance with the present invention.

In summary, several embodiments of high-power, IC frequency-converted, OPS-lasers in the accordance with the present invention have been described above. Generally, embodiments of the inventive laser can generate second, third or fourth harmonic output-power from fundamental radiation at a power of 100 mW or greater, and even at 1 W or greater. These high-harmonic output powers can be achieved in single axial mode or TEM_{00} operation with a beam-quality of less than about twice the diffraction-limit. Particularly notable is the ability of the inventive lasers to generate UV output-radiation at these high output-powers, more particularly, at better than one percent pump-to-harmonic efficiency by second-harmonic generation from fundamental radiation in a 700 nm to 800 nm wavelength ranges.

The inventive OPS-lasers, can provide a means of generating wavelengths, in a true CW mode of operation, which can closely match the optimum wavelength for many laser applications, in fields such as medicine, optical metrology, spectroscopy, optical lithography, and precision laser machining. By way of example, an inventive OPS laser can efficiently produce CW output radiation in the 590 to

WHAT IS CLAIMED IS:

1. A laser, comprising:

a laser-resonator (22F) having a resonator axis and being terminated by first and second mirrors (28F,30);

an OPS-structure (32) located within the resonator and having a gain-structure (34) surmounting a mirror-structure, said gain-structure including a plurality of active layers having pump-light-absorbing layers therebetween, said active layers having a composition selected to provide emission of electromagnetic radiation at a predetermined fundamental-wavelength between about 425 nanometers and 1800 nanometers when optical-pump light is incident on said gain-structure, and said mirror-structure including a plurality of layers of alternating high and low refractive index and having an optical thickness of about one-quarter wavelength of said predetermined wavelength;

an optical arrangement (40) for delivering said pump-light (42) to said gain-structure, thereby causing fundamental laser-radiation having said fundamental-wavelength to oscillate in said laser-resonator;

a heat-sink arrangement (36) for cooling said OPS-structure;

one or more optically-nonlinear crystals (50) located in said laser-resonator and arranged for frequency-multiplying said fundamental laser-radiation thereby providing frequency-multiplied radiation having a wavelength which is a fraction of said fundamental-wavelength; and

said laser-resonator, said optically nonlinear-crystal, said OPS-structure, said heat-sink arrangement and said optical pump-light-delivering

5. The laser of any of claims 1-4, wherein said laser-resonator has an optical length of at least about 5 cm.

6. The laser of any of claims 1-4, wherein said frequency-multiplied radiation is delivered in a single axial-mode.

7. The laser of any of claims 1-4 wherein, said active layers of said gain structure are selected from the group of semiconductor compounds consisting of $In_xGa_{1-x}As_yP_{1-y}$, $Al_xGa_{1-x}As_yP_{1-y}$, and $In_xGa_{1-x}N$ where $0.0 \leq x \leq 1.0$ and $0 \leq y \leq 1$.

8. The laser of claim 7 wherein, said active layers of said gain structure have a composition of $In_xGa_{1-x}As$ where $0.0 < x < 1.0$ and x is selected such that said fundamental wavelength is between about 900 and 1050 nanometers, and said gain structure includes separator layers between said active layers, said separator layers having a composition $GaAs_yP_{1-y}$.

9. The laser of claim 8 wherein, said high refractive index layers of said mirror-structure have a composition GaAs and said low refractive index layers of said mirror-structure have a composition $AlAs_yP_{1-y}$ where $0.0 < y < 1.0$.

10. The laser of claim 7 wherein, said active layers of said gain structure have a composition of $InxGa1_{-x}P$ where $0.0 < x < 1.0$ and x is selected such that said fundamental wavelength is between about 700 and 900 nanometers, and said gain structure includes separator layers between said active layers said separator layers having a composition $In_yGa_{1-y}As_zP_{1-z}$ where $0.0 < y < 1.0$ and $0.0 < z < 1.0$.

16. The laser of claim 15, wherein said wavelength-selective element is a birefringent filter.

17. The laser of claim 15, wherein said wavelength-selective element is an etalon.

18. The laser of any of claims 1-4, wherein said heat-sink arrangement includes an actively-cooled member and said actively-cooled member has a diamond layer in thermal contact therewith, said mirror-structure of said OPS-structure OPS structure being in thermal contact with said diamond layer.

19. The laser of claim 18, wherein said actively-cooled member is a microchannel-cooler.

20. The laser of any of claims 1-4 wherein said optical arrangement for delivering said pump-light to said gain-structure includes at least one optical-lightguide for transporting pump-light from a source thereof to an optical-focusing arrangement for focusing said pump-light, said optical-focusing including at least one lens.

21. The laser of claim 20 wherein said at least one lens is a radial-gradient-index lens.

22. The laser of claim 21 wherein said optical-focusing arrangement includes two radial-gradient-index lenses.

23. The laser of claim of any of claims 1-4 wherein any of said one or more optically-nonlinear crystals is a crystal of a material selected from the

distance at least three times the longest dimension of said predetermined pump-light-delivery area to minimize parasitic lateral oscillation of fundamental radiation therein.

29. The laser of claim 27, wherein said OPS-structure is in the form of a rectangular chip having an emitting-face and having two pairs of parallel end-faces at right angles to said emitting-face, said parallel end-faces being roughened to prevent spectral reflection of fundamental radiation therefrom, thereby minimizing said parasitic lateral oscillation.

30. The laser of any of claims 1-4, wherein, in said mirror-structure, the refractive index, thermal conductivity, and number of said layers thereof are selected to provide maximum thermal conductivity of heat-generated in said gain-structure to said heat-sink arrangement, while providing sufficient reflectivity to cause build-up of fundamental radiation in said laser resonator.

31. The laser of any of claims 1-4, wherein said mirror-structure further includes a layer of a highly-reflective metal, said metal-layer being closest to said heat-sink arrangement.

32. The laser of any of claims 1-4, wherein said pump-light is delivered on said gain-structure of said OPS-structure in a predetermined pump spot-size and said resonator is configured such that the spot-size eat said gain structure of said oscillating fundamental laser-radiation is about equal to said pump spot-size.

said second mirror is said mirror-structure of said first OPS-structure.

36. The laser of claim 34 wherein said laser-resonator is configured as a folded resonator (142), said first OPS-structure (32X) includes a mirror-structure (30X) surmounted by said gain-structure and said mirror-structure of said first OPS-structure serves as a fold-mirror for folding said laser resonator.

37. The laser of claim 36 further including a second OPS-structure (32), said second OPS-structure having a gain-structure (30) located in said laser resonator and including a plurality of active layers having separator layers therebetween said active layers having a composition selected to provide emission of electromagnetic radiation at said predetermined fundamental-wavelength, the laser further including a second optical arrangement for delivering said pump-light to said gain-structure of said second OPS-structure, and wherein said mirror structure (30) is said second mirror.

38. The laser of any of claims 36 and 37, wherein said longitudinal axis of said laser-resonator is folded by said mirror-structure of said first OPS-structure at an angle such that said laser-radiation oscillating in said laser-resonator is incident on said first OPS-structure at an angle selected to minimize interference therein between counterpropagating beams of said oscillating laser radiation.

composition $In_yGa_{1-y}As_zP_{1-z}$ where $0.0 < y < 1.0$ and $0.0 < z < 1.0$.

46. The laser of claim 45 wherein, said high refractive-index layers of said mirror-structure have a composition $In_pAl_{1-p}P$, $0.0 < p < 1.0$, and said low refractive-index layers of said mirror-structure have a composition $Al_qGa_{1-q}As$, where $0.0 < q < 1.0$.

47. The laser of claim 41 wherein, said active layers of said gain-structure have a composition of $In_xAs_{1-x}P$ where $0.0 < x < 1.0$ and x is selected such that said fundamental-wavelength is between about 700 and 900 nanometers, and said separator layers have a composition $Al_yGa_{1-y}As$ where $0.0 < y < 1.0$.

48. The laser of claim 47, wherein said high refractive-index layers and said low refractive-index layers of said mirror-structure are layers of respectively high and low refractive-index dielectric materials transparent to said fundamental-wavelength.

49. The laser of claim 48, wherein said high refractive-index material is zinc selenide and said low refractive-index material is aluminum oxide.

50. The laser of any of claims 34-36, wherein said active layers of said gain-structure have a gain-bandwidth and said laser-resonator further includes a wavelength-selective element (52) configured and arranged to select said wavelength of fundamental laser-radiation within said gain-bandwidth.

parasitic lateral oscillation of fundamental radiation therein.

59. The laser of claim 58, wherein said first OPS-structure is in the form of a rectangular chip (119) having an emitting-face, said pump-light being delivered onto said emitting-face in a predetermined area thereon, said chip having two pairs of parallel end-faces (120) at right angles to said emitting-face, said parallel end faces being spaced apart by a distance at least three times the longest dimension of said predetermined pump-light-delivery area.

60. The laser of claim 58, wherein said first OPS-structure is in the form of a rectangular chip having an emitting-face and having two pairs of parallel end-faces at right angles to said emitting-face, said parallel end-faces being roughened to prevent spectral reflection of fundamental radiation therefrom, thereby preventing said parasitic lateral oscillation.

61. The laser of any of claims 35 and 36, wherein, in said mirror-structure, the refractive-index, thermal conductivity, and number of said layers thereof are selected to provide maximum thermal conductivity of heat-generated in said gain-structure to said heat-sink arrangement, while providing sufficient reflectivity to cause build-up of fundamental radiation in said laser-resonator.

62. The laser of any of claims 35 and 36, wherein said mirror-structure further includes a layer of a highly-reflective metal, said metal-layer being closest said heat-sink arrangement.

into said coaxial path by a fourth mirror (72) located between said first mirror and said second mirror, said fourth mirror being reflective for said frequency-doubled radiation and transmissive for said fundamental laser-radiation, and said coaxial path extending between said first and fourth mirrors.

65. The laser of any of claims 63 and 64, further including a second optically-nonlinear crystal (62) located in said coaxial path and arranged for mixing said fundamental laser-radiation and said frequency-doubled radiation, thereby generating frequency-tripled radiation (3H).

66. The laser of claim 64 wherein, said coaxial path is folded at an angle by a fifth mirror (26) located between said first and third mirrors, said fifth mirror being reflective for said frequency-doubled-radiation and said fundamental laser-radiation and transmissive for said frequency-tripled radiation said first optically-nonlinear crystal being located between said fourth and fifth mirrors, said second optically-nonlinear crystal being located between said first and fifth mirrors and said fifth mirror serving as an output coupling mirror for delivering said frequency-tripled radiation from said laser.

67. The laser of any of claims 63-66, wherein said active layers of said gain-structure have a gain-bandwidth including said fundamental-wavelength and said first laser-resonator includes a wavelength-selective element (52) located outside said coaxial path and configured to select said fundamental-wavelength of laser-radiation from within said gain-bandwidth.

of said frequency-doubled radiation, thereby generating frequency-quadrupled radiation (4H).

74. The laser of claim 73 wherein, said axis of said second resonator outside said coaxial path is folded at an angle by a seventh mirror (94) located between said fourth and fifth mirrors, said seventh mirror being reflective for said frequency-doubled-radiation and transmissive for said frequency-quadrupled radiation, said first optically-nonlinear crystal being located between said fifth and sixth mirrors, said second optically-nonlinear crystal being located between said fourth and seventh mirrors and said seventh mirror serving as an output coupling mirror for delivering said frequency-quadrupled radiation from said laser.

75. The laser of any of claims 72-74, wherein said active layers of said gain-structure have a gain-bandwidth including said fundamental-wavelength and said first laser-resonator includes a wavelength-selective element (52) located outside said coaxial path and configured to select said fundamental-wavelength of laser-radiation from within said gain-bandwidth.

76. The laser of claim 75, wherein said wavelength-selective element is a birefringent filter.

77. The laser of claim 75, wherein said wavelength-selective element is an etalon.

78. The laser of claims 72-75 wherein the length of said second resonator is adjustable (76)

gain-structure (34) incorporated into a laser resonator (22), said gain-structure including a plurality of active layers having separator layers therebetween, said active layers having a composition selected to provide generation by said laser resonator of fundamental laser-radiation having a wavelength which is a selected integer multiple of a predetermined wavelength within the characteristic absorption band of the material when optical pump-light is delivered to said gain-structure, and said OPS laser including one or more optically-nonlinear crystals (50, 62) arranged to multiply the frequency of said fundamental radiation by said selected integer multiple, thereby generating frequency-multiplied radiation having said predetermine wavelength;

(b) delivering optical pump-light to said gain-structure, thereby generating said frequency multiplied radiation;

(c) coupling said frequency multiplied radiation out of said OPS laser as output radiation; and

(d) delivering said output radiation to the material.

86. The method of claim 85 wherein said output radiation is delivered via at least one of a lightguide, an articulated arm, and an optical focussing system.

87. The method of any of claims 85 and 86 wherein said output radiation coupled out of the laser has a power greater than about has a power greater than about 100 mW.

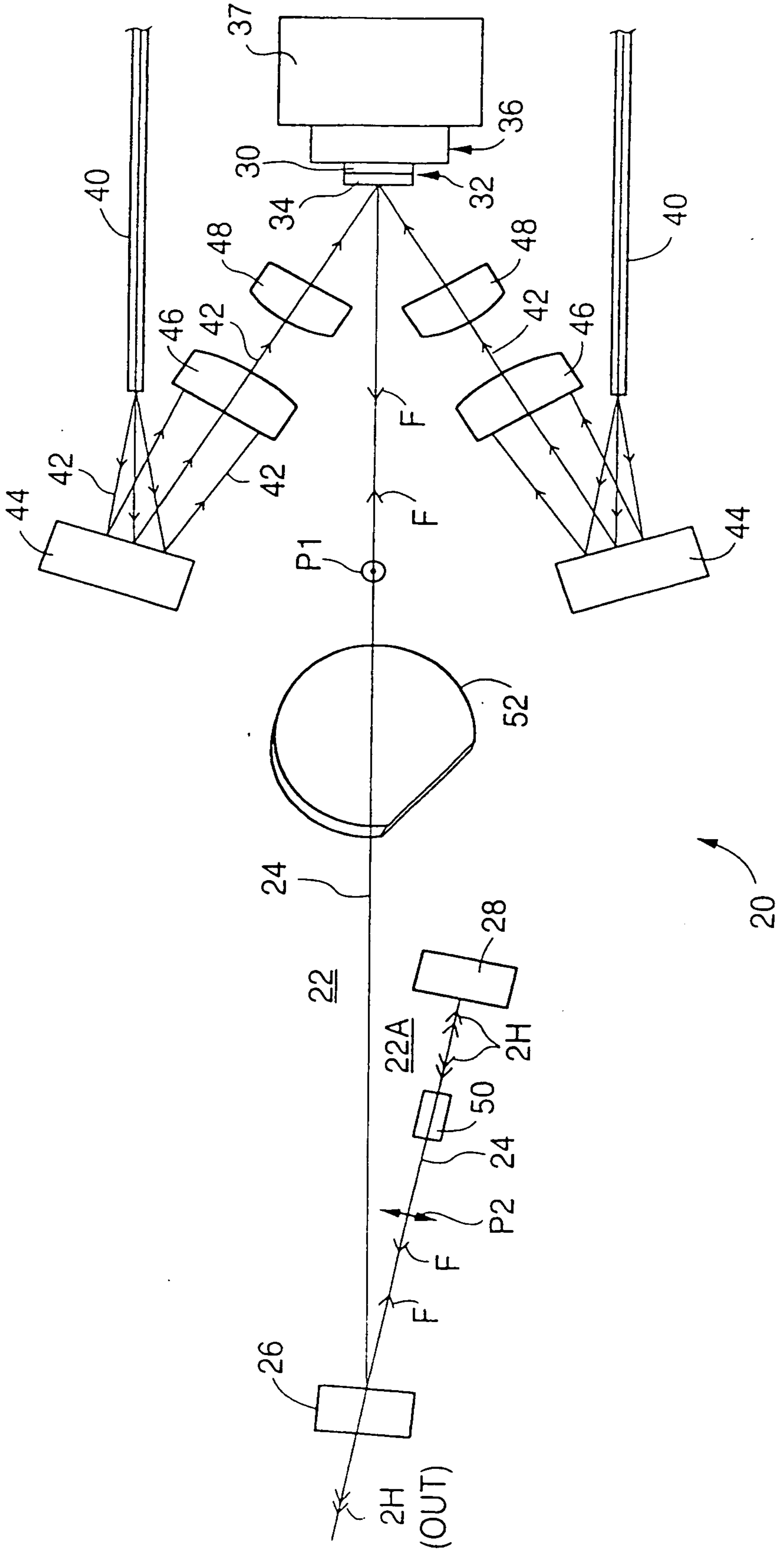
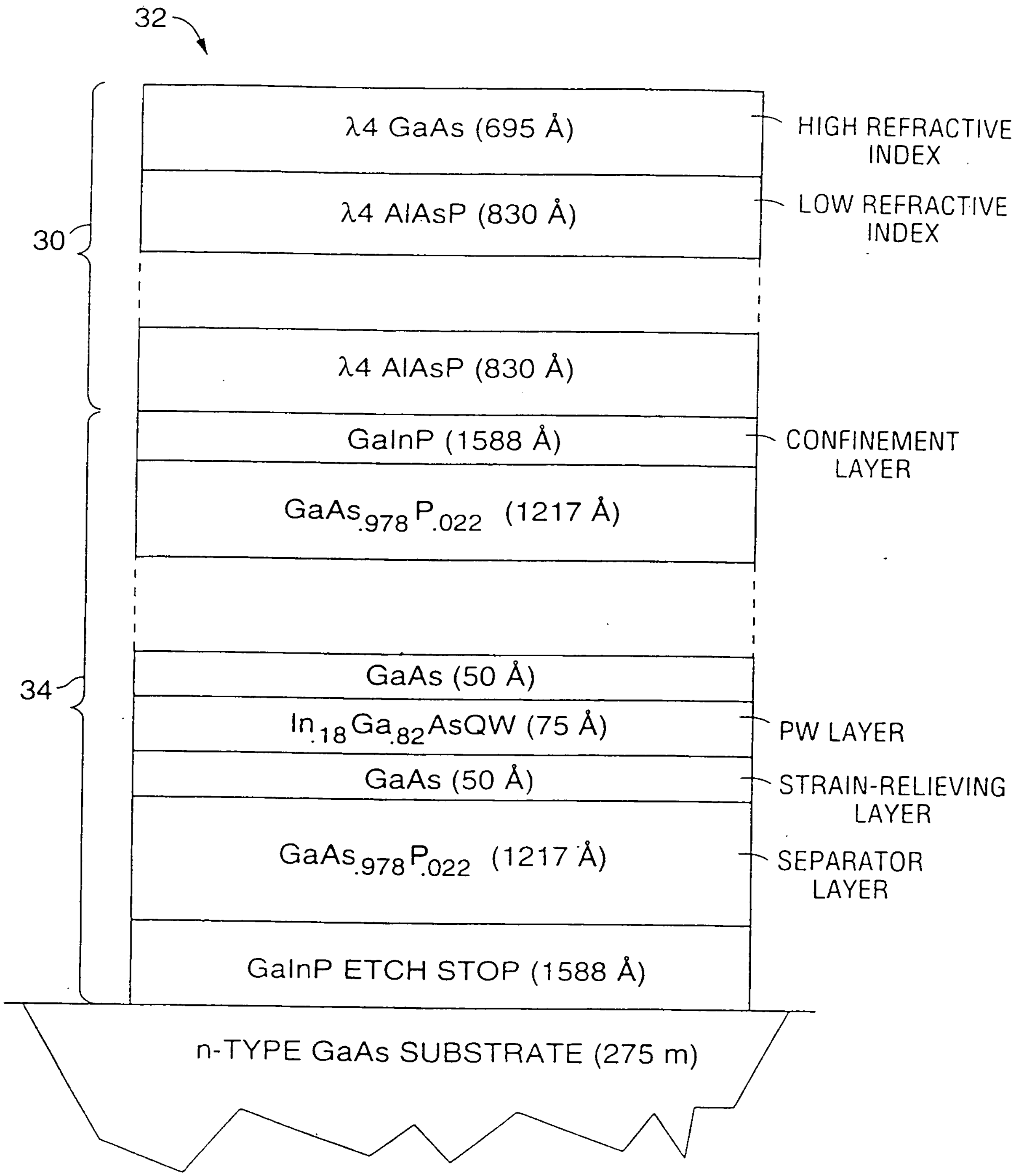


FIG. 1



32
30
34
λ4 GaAs (695 Å)
HIGH REFRACTIVE INDEX
λ4 AlAsP (830 Å)
LOW REFRACTIVE INDEX
λ4 AlAsP (830 Å)
GaInP (1588 Å)
CONFINEMENT LAYER
GaAs.978P.022 (1217 Å)
GaAs (50 Å)
In.18Ga.82AsQW (75 Å)
PW LAYER
GaAs (50 Å)
STRAIN-RELIEVING LAYER
GaAs.978P.022 (1217 Å)
SEPARATOR LAYER
GaInP ETCH STOP (1588 Å)
n-TYPE GaAs SUBSTRATE (275 m)

FIG. 3

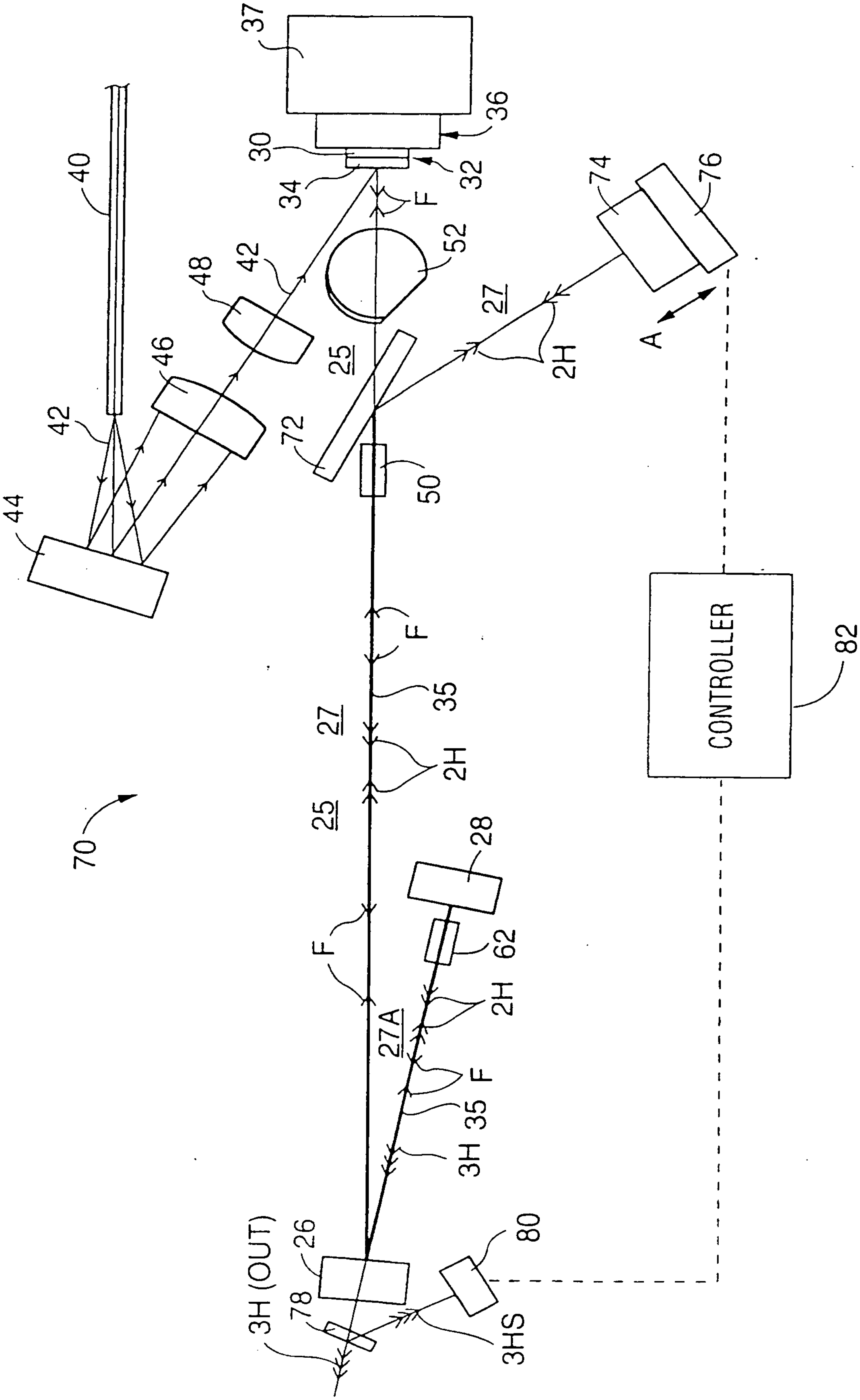

37
36
30
32
34
F
40
42
48
52
74
76
27
25
2H
A
46
72
50
44
35
70
28
62
27A
3H
3H (OUT)
26
78
80
3HS
CONTROLLER
82

FIG. 5

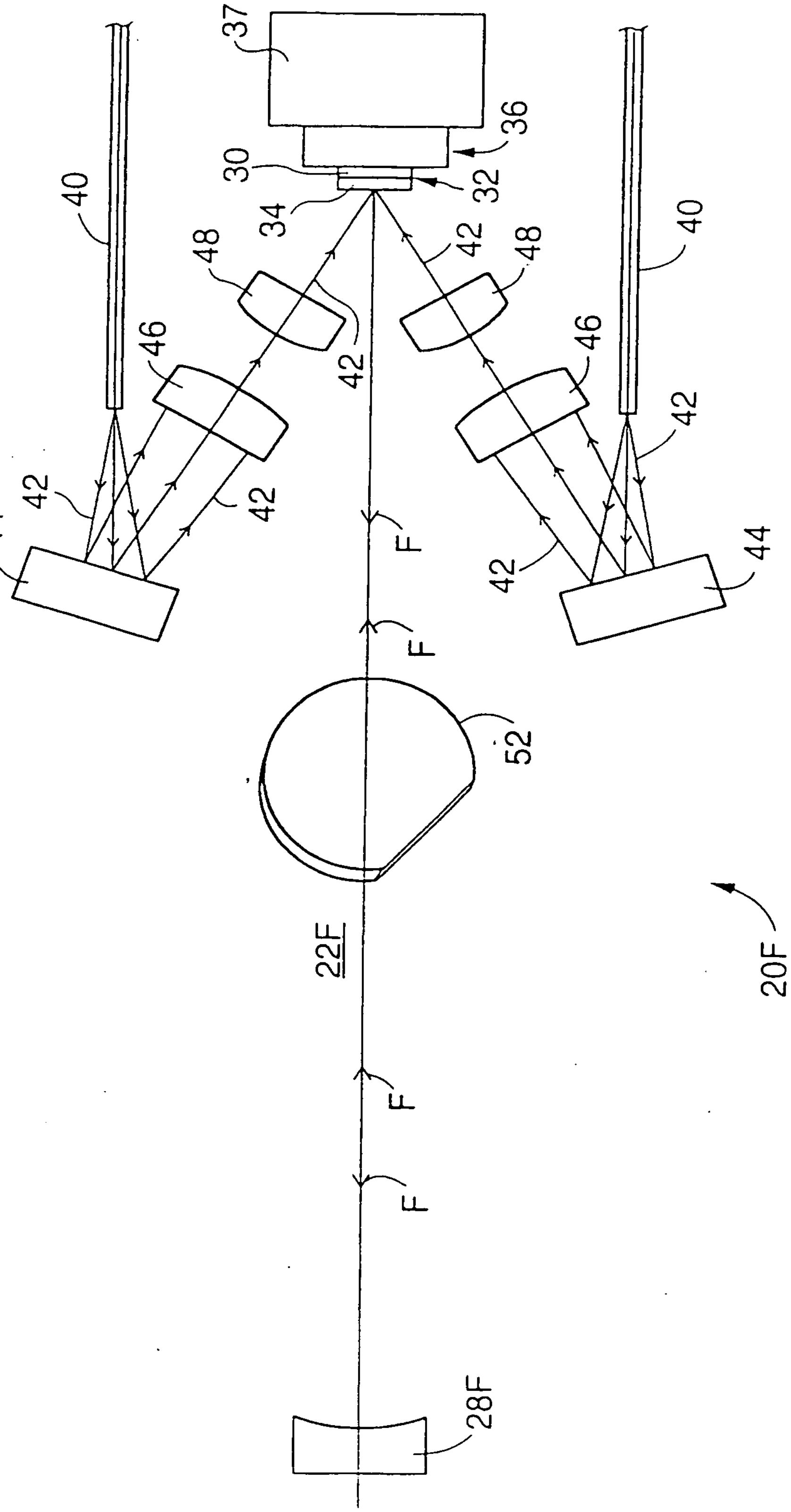


FIG. 7

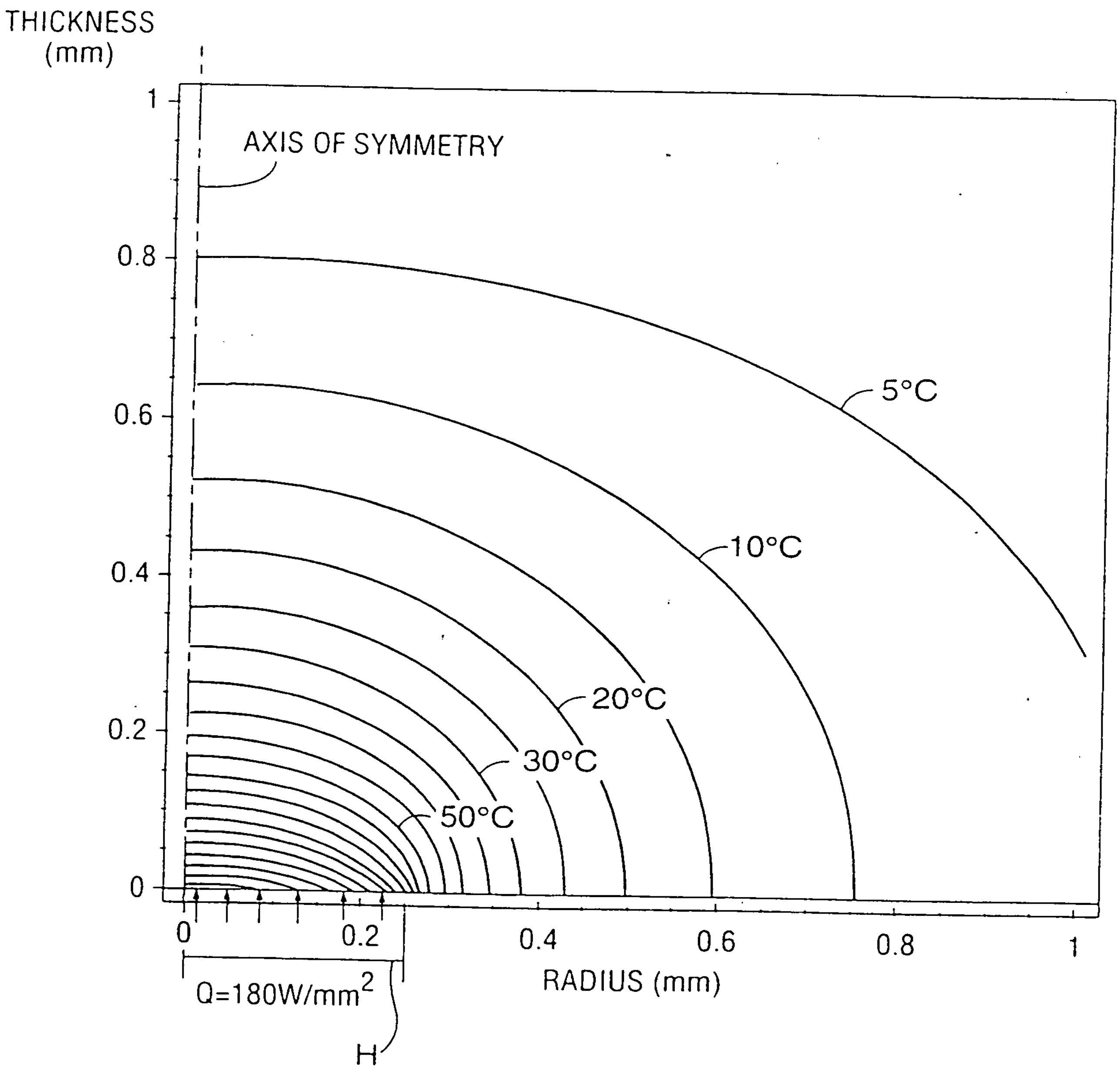

THICKNESS
(mm)
1
AXIS OF SYMMETRY
0.8
5°C
0.6
10°C
0.4
20°C
0.2
30°C
50°C
0
0
0.2
0.4
0.6
0.8
1
RADIUS (mm)
Q=180W/mm^2
H

FIG. 9

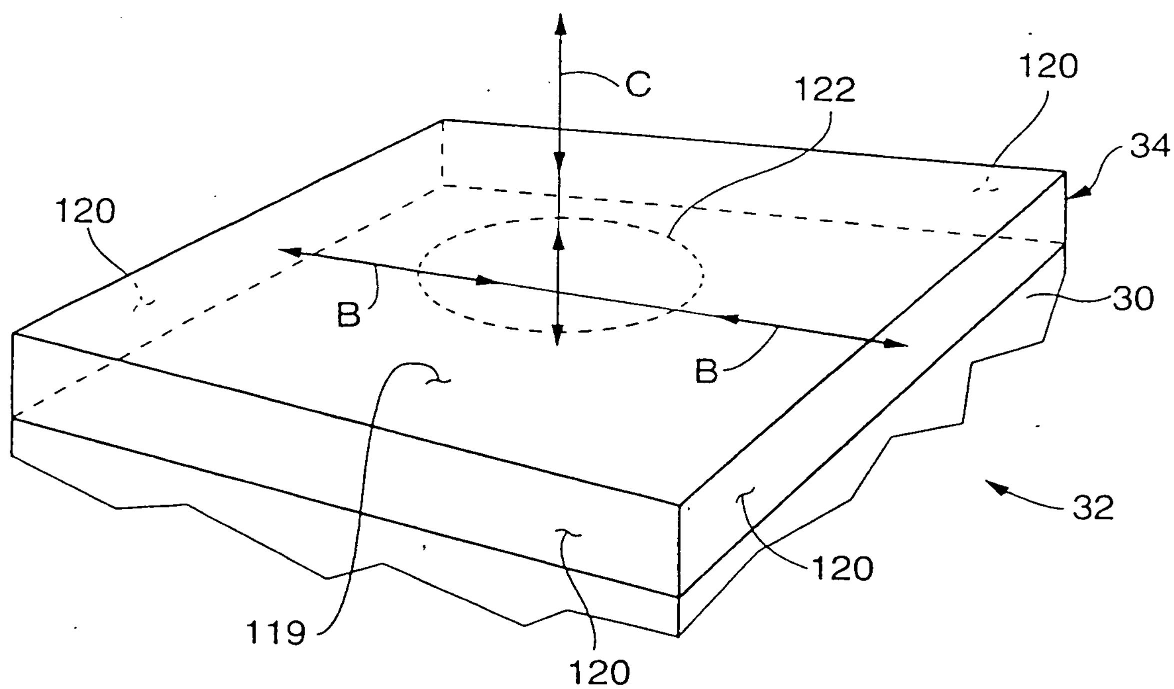


FIG. 11

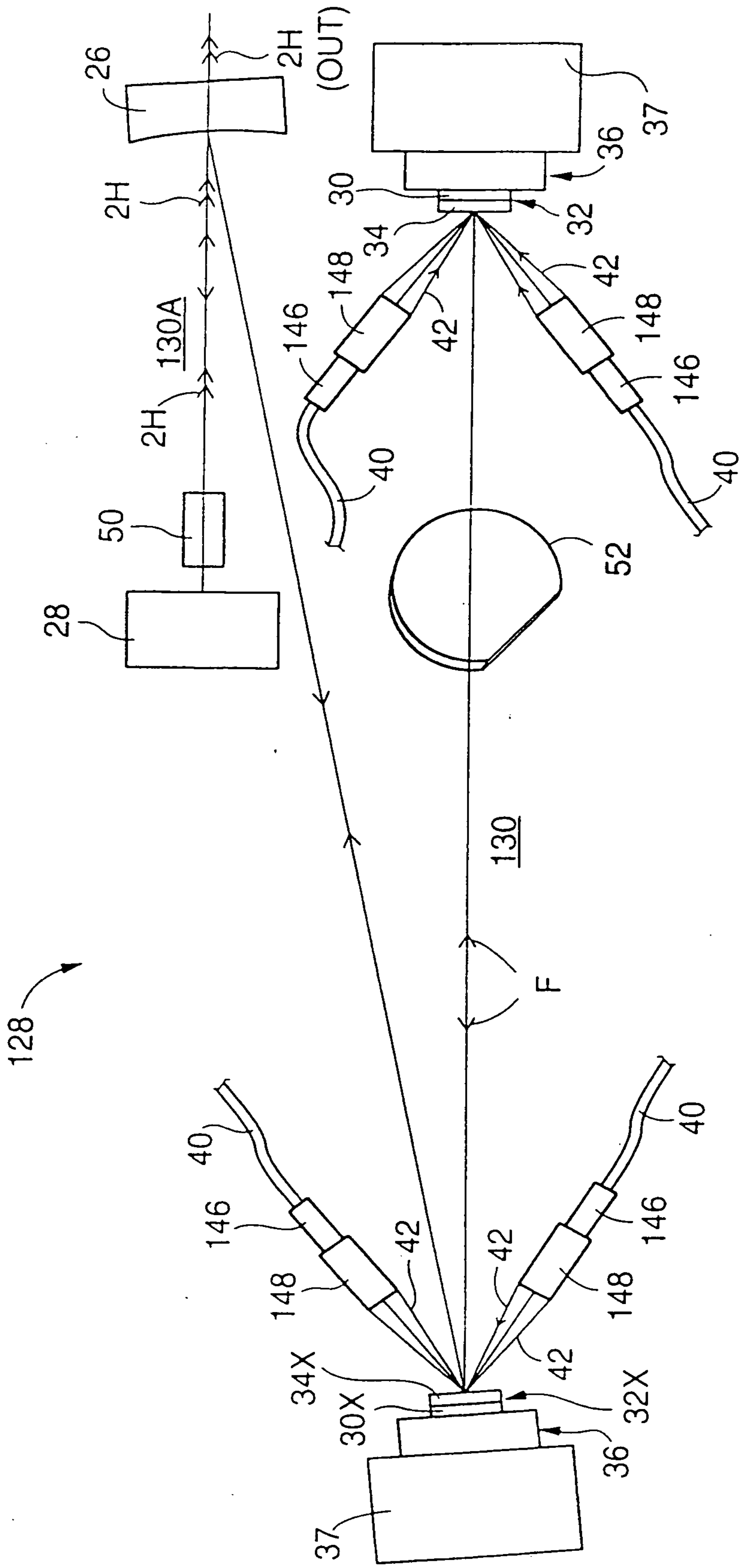

26
2H
(OUT)
37
36
30
32
34
2H
130A
2H
50
28
148
146
42
40
52
130
F
128
34X
30X
32X

FIG. 13

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 99/24303

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01S5/024 H01S5/183 H01S5/14 H01S5/04 H01S3/109
H01S3/108

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01S G02F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	KUZNETSOV M ET AL: "HIGH-POWER (0.5-W CW) DIODE-PUMPED VERTICAL-EXTERNAL-CAVITY SURFACE-EMITTING SEMICONDUCTOR LASERS WITH CIRCULAR TEM00 BEAMS" IEEE PHOTONICS TECHNOLOGY LETTERS,US,IEEE INC. NEW YORK, vol. 9, no. 8, page 1063-1065 XP000699799 ISSN: 1041-1135 cited in the application	34,35, 41,44, 45,61
A	page 1063, right-hand column, paragraph 2 -page 1064; figure 2	1,7,8, 18,53

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
18 February 2000	25/02/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Stang, I

2

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 99/24303

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